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Possible climate change evidence in ten Mexican watersheds

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ABSTRACT

This paper suggests possible evidence of climate change in Mexico at the watershed level, based solely on historical data. The official Mexican climate dataset was used to find the best set of stations for each watershed. Maximum and minimum temperatures and rainfall in ten watersheds are analyzed from 1970 to 2009. Maximum temperature trends show a significant increment in most of these watersheds. Furthermore, Daily Temperature Range (DTR) exhibits a positive trend (increments), thus implying an increase in temperature extremes. This study also shows that the difference between maximum and minimum monthly temperature trends is negatively correlated with monthly precipitation trends. As a result, land-use and land-cover changes could be the main drivers of climate change in the region.

1. Introduction

Recent observations presented in various studies have already shown an increase in the global surface temperature (IPCC, 2007, 2013). In order to understand and better assess how these changes may affect the planet and its life forms, temperature impact scenarios have been generated. Climate change's direct effect on human economic activities disproportionately affects poor and marginalized groups in developing nations. Moreover, the availability and quality of natural resources and ecosystem services are also affected by climate change.

Mexico's general climate features and changes have already been described in the past (Mosiño and García, 1974; Metcalfe, 1987; Jáuregui, 1997).

The principal large-scale atmospheric features that define Mexico's climate are, in addition to the Intertropical Convergence Zone (ITCZ), the trade winds, the subtropical high-pressure belt, and the Westerlies (Metcalfe, 1987). It is also known that the main drivers of inter-annual climate variability for this region are related to the dynamics of the ITCZ (Metcalfe, 1987; Waliser and Gautier, 1993), El Niño Southern Oscillation (ENSO) (Cavazos and Hastenrath, 1990; Dilley, 1996; Pavia and Graef, 2002; Magaña et al., 2003), Madden-Julian Oscillation (MJO) (Maloney and Hartmann, 2000; Aiyyer and Molinari, 2008; Camargo et al., 2009), Pacific Decadal Oscillation (PDO) (Goodrich, 2007; Arriaga-Ramírez and Cavazos, 2010), North Atlantic Oscillation (NAO) (Ropelewski and Halpert, 1986; Portis et al., 2001), and the Atlantic Multidecadal Oscillation (AMO) (Englehart and Douglas, 2004). Other key features, at different frequencies and geographic scales, include the Caribbean and Gulf of California low-level jets (CLLJ and GCLLJ, respectively) (Stensrud, 1996; Amador, 1998; Mo et al., 2005; Wang, 2007; Whyte et al., 2008). Year by year, the interaction of all these elements drives the activity of the North American monsoon (NAM) (Douglas et al., 1993; Adams and Comrie, 1997; Barlow et al., 1998; Zhu and Lettenmaier, 2007), the midsummer drought (MSD) (Magaña et al., 1999), the Atlantic and Pacific tropical cyclones (Maloney and Hartmann, 2000; Aiyyer and Molinari, 2008; Camargo et al., 2009; Redmond and Abatzoglou, 2014), the easterly waves and the cold fronts in Mexico.

Although data coverage is only good in some parts of Mexico (Prieto-González et al., 2008), some studies have already been conducted on trends and evidence of climate change in the region (Redmond and Abatzoglou, 2014).

Metcalfe (1987), using archaeological and historical evidence, was the first researcher who tried "to fill the gap" of data by looking at climate changes in Mexico over the last 2000 years. Wet, dry and cold periods were identified prior to the existence of systematic

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instrumental records. Jáuregui (1979), using as a basis a 90-year instrumental record for precipitation, identified climate cycles that showed a drier period from 1878 to 1900, a wetter period from 1900 to 1930, and again a drier period from 1940 to early 1950s. During the second half of the 1950s and the 1960s, precipitation increased again in central and southern Mexico, but drought prevailed in the northern part of the country (Metcalfe, 1987). Years later, Jáuregui (1997) studied climate changes in Mexico since the beginning of the instrumental record. He also highlights the drought conditions prior to the 1810 and 1910 revolutions. These droughts were synchronous with the declining strength of the Northern Hemisphere zonal circulation, characterized by increased prominence of meridional flow, mid-latitude cold winters, and deep penetration of Arctic masses into the tropics. The southerly shift of major mid-latitude circulation features during the 1960s may be related to cooler and drier conditions in eastern Mexico. The three longest uninterrupted records come from the Tacubaya, Guadalajara and Chihuahua stations, and there was a significant decrease in measurements during the 1980s due to the country's economic crisis (Prieto-González et al., 2008).

Other studies have already examined long-term trends in the past for the Mexican region. For instance, Jáuregui and Klaus (1976) described long-term fluctuations in rainfall in terms of the circulation patterns aloft. Other researchers have shown that the Diurnal Temperature Range (DTR = maximum−minimum temperature) trends over Mexico were positive in the recent past, mainly because maximum temperatures are warming at a significantly higher rate than minimum temperatures (Englehart and Douglas, 2005; Pavia et al., 2009; IPCC, 2013). DTR has been used widely as an indicator of potential climate change. By analyzing high-resolution Climatic Research Unit Time Series (CRU TS 3.1) data, Redmond and Abatzoglou (2014) found that the 1990s and 2010s are the warmest decades of the last 110 years. Easterling et al. (2000) indicated that all of North America (including Mexico) showed a significant positive trend in heavy precipitation events in recent decades. An assessment of sea-surface temperature change signals in the seas off Mexico shows mostly cooling in the Pacific Ocean (during the past decade) and warming in the Gulf of Mexico and the Caribbean (for the past three decades) (Lluch-Cota et al., 2013).

On the regional scale, there are some trend analyses in northwestern Mexico (Arriaga-Ramírez and Cavazos, 2010; García-Cueto et al., 2010, 2013; Gutiérrez-Ruacho et al., 2010), which is by far the most studied region in the country with respect to climate.

Only a handful of studies have concentrated on studying long-term trends in watersheds around Mexico. However, most of these studies are focused on hydrology. By using modeling to complete data series, Zhu and Lettenmaier (2007) argued that long-term mean evapotranspiration is realistically reproduced in 14 small river basins spanning Mexico as a whole. In addition, Liu et al. (2013) calculated long-term evapotranspiration and runoff trends in the drainage basins of the Gulf of Mexico during 1901−2008.

The present study focuses on analyzing precipitation and surface temperature trends in the ten watersheds with the best-quality data found around Mexico.

2. Data and methods

With the aim of better understanding Mexico's temperature and rainfall trends, 40 years of climatological data (from 1970 to 2009) were analyzed for ten watersheds (Fig. 1). From the existing network, operated by the National Meteorological Service, a group of ten "best" climatological stations (Fig. 1), one in each watershed, was selected (Computerized Climate database [CLICOM]). The variables analyzed were pluvial precipitation, and maximum and minimum daily temperature.

The criteria used for watershed selection included geographic location (spatial distribution), representativeness and vulnerability (as defined by IPCC 2015). The geographic distribution of watersheds is related to generally accepted climate zoning for the country. It is widely agreed that Mexico's typical climates are generally dry and hot in the north, temperate in the center, and warm and moist in the south. Representativeness was used to select watersheds that exhibit climatological behavior typical of their respective climate zone. In other words, watersheds in transition zones, or those with areas in more than one climate zone, were assigned lower scores. The representativeness criterion is related to data quality; the selected watersheds should have at least ten climatological stations with at least 70% of reliable data, per decade, for the 1970−2009 period.

In the watersheds, the vulnerability criterion refers to the presence of populations living below the poverty line and those classified as vulnerable to the impacts of climate change.

Once the watersheds and the climatological stations were selected, it was necessary to implement quality-control mechanisms and to revise the data's internal consistency. Thereafter, a total of 100 stations were selected. These stations are distributed in the selected watersheds, as shown in Fig. 1.

3. Results and discussion

In this study, all averages at the watershed level, for each variable, are calculated using the Thiessen (Okabe et al., 2000) weighted-average method, as follows:

$$\overline{Y}_w = \frac{1}{A_w}\sum_{i=1}^{n} A_{pi} Y_i$$

where A is the area, $_w$ and $_p$ refer to the watershed and Thiessen polygon, Y is the variable, and $_i$ refers to each climatological station of the watersheds, so that Y_w is the Thiessen weighted-average variable.

3.1. Monthly analysis

3.1.1. Monthly means

First, monthly rainfall as well as maximum and minimum temperature averages for each of the climatological stations were calculated (not shown). The watersheds' mean values per variable were then calculated using the Thiessen method (Figs. 2 and 3).

Analysis of these estimates led to the following observations: The seasonal distribution of maximum and minimum temperatures in each watershed has a well-defined annual signal. Maximum temperature values show a simple wave pattern with low values in December and January and high values in May. During the summer months (June/July/August), average maximum temperatures decrease due to the influence of ITCZ, which marks the beginning of the rainy season in the watersheds of central and southern Mexico (Fig. 2d−j).

Papaloapan, the watershed at the lowest latitude, shows little temperature variation throughout the year because it is the most tropical region in this study (Fig. 2j). The coldest watersheds, located in central Mexico, are characterized by high mountains and the country's highest average altitude (Figs. 1, 2g and i).

In general, average monthly rainfall in the selected watersheds is lower in the north and increases at lower latitudes (Fig. 3), with the exception of the Laja and Moctezuma watersheds (Fig. 3h and i). In all watersheds, the highest average monthly rainfall is observed during summer (June−September). In the Yaqui watershed (Fig. 3a), maximum climatological rainfall is in July, with a relative

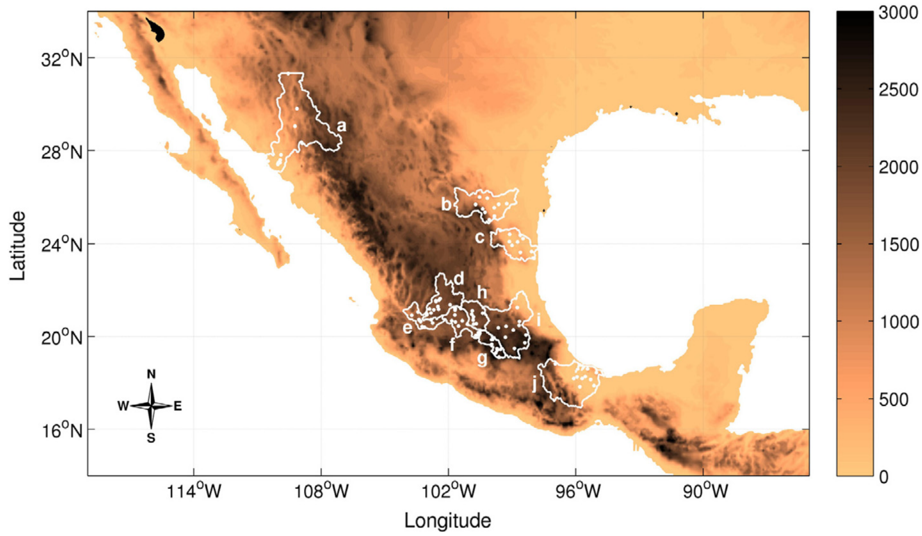

Fig. 1. Study area. The ten watersheds and the selected climatological stations are highlighted in white. The map also includes topography: the right bar shows the color scale in meters above sea level. The names of the watersheds are, in order, (a) Yaqui, (b) Bravo San Juan, (c) Soto la Marina, (d) Verde Grande, (e) Santiago Guadalajara, (f) Lerma Salamanca, (g) Lerma Toluca, (h) Laja, (i) Moctezuma, and (j) Papaloapan.

maximum in December–January due to frontal activity. The two watersheds in the northeastern region—Bravo San Juan and Soto la Marina (Fig. 3b and c)—show the typical bimodal rainfall pattern for the region, with a maximum value in September.

With the exception of the Moctezuma watershed (Fig. 3i), the central watersheds have maximum climatological rainfall in July (Fig. 3d–h), due to local convection generated by the ITCZ. Rainfall in the Moctezuma and Papaloapan watersheds is modulated by the mid-summer drought, with a peak in September due to tropical cyclone activity (Fig. 3i and j).

3.1.2. Monthly trends

Rainfall, as well as maximum and minimum temperature standardized anomalies, for each station were calculated by using monthly averages and standard deviations (Wilks, 2006). Standardized anomaly data were integrated by watershed using the Thiessen weighted-average method.

The non-parametric Mann–Kendall test was applied to evaluate trends and their significance levels (Mann, 1945; Kendall, 1975). Because, high-quality data were previously obtained for each region, a simple least-square fit was used to compute the slope of monthly temperature and rainfall trends. The subsequent analyses will use a 90% significance level for maximum and minimum temperatures, and 70% for precipitation.

Average monthly maximum temperature anomalies exhibit positive (monthly) trends in the ten watersheds analyzed. Trends are less than 0.4 per decade in all watersheds (Fig. 4). The most significant maximum temperature trends were found during the wet season in Mexico (May–September). Most of the tropical ($<23°$ latitude) watersheds show a significant relative maximum in February (Fig. 4d–j).

The largest positive trends in maximum temperature are from May to August, and are larger than those for minimum temperature, in accordance with projected climate changes estimated for Mexico (Montero-Martínez et al., 2013).

Compared to maximum temperature, minimum temperature shows fewer significance-level results. Most relevant trends are positive (from June to September), with the exception of the Lerma Toluca watershed, which has a negative trend. In the northern watersheds, the monthly change in average minimum temperature trends (in all stations in each watershed) shows a behavior similar to that of the maximum temperature. It is worth noting that, although the significance levels are not very high, nearly all watersheds (with the exception of Yaqui) show a relative maximum trend in February and a minimum in December. Trends are less than 0.4 per decade in all watersheds (Fig. 4) and include some negative values.

As previously mentioned, the maximum monthly temperature trends found here are generally larger than those of minimum temperature. This implies that monthly DTR trends are mostly positive for the ten watersheds (Fig. 4). This result is in close agreement with previous work for Mexico during the period analyzed here (Englehart and Douglas, 2005; Pavia et al., 2009). For instance, Englehart and Douglas found a contrasting behavior of DTR trends when they analyzed the 1940–1970 period (negative trend) versus 1971–2001 (positive trend). In fact, the expected response, due solely to global warming, is that DTR trends tend to be negative in large portions of the world (Easterling et al., 1997). Englehart and Douglas attribute part of the observed DTR behavior in recent decades to regional land-use and land-cover changes (LCCs) in Mexico.

Precipitation trend analyses do not show a defined large-scale pattern. This means that precipitation trends are driven by regional or local factors. As mentioned above, a positive gap between maximum and minimum temperature trends implies a positive DTR trend. In addition, the difference between maximum and minimum monthly temperature trends was calculated. It showed a negative correlation with the precipitation trend (Fig. 5). This feature is clearly found for most of the central watersheds in December. This result is in agreement with the Englehart and Douglas study (2005), which highlights inverse correlations of DTR with precipitation. This suggests that LCCs could be the main driver of climate change in the region.

3.2. Annual analysis

3.2.1. Annual means

This section briefly presents the results found at the annual time-resolution scale. Annual temperature averages per watershed are obtained as follows:

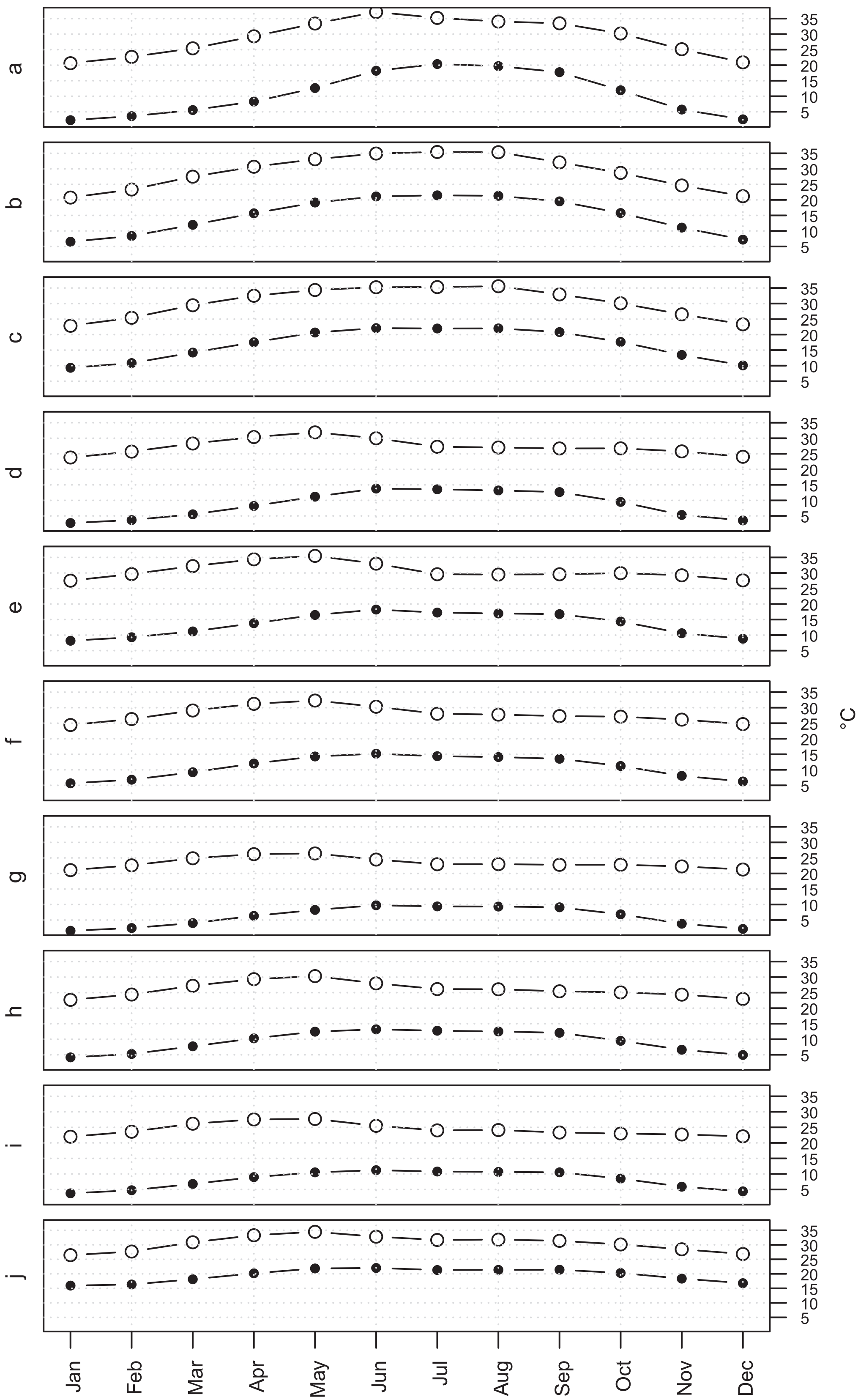

Fig. 2. Monthly minimum and maximum temperature mean (°C) for the ten watersheds with a base period from 1970 to 2009. The watersheds follow the same order as that of Fig. 1. Dark and clear dots refer to the minimum and maximum temperature, respectively.

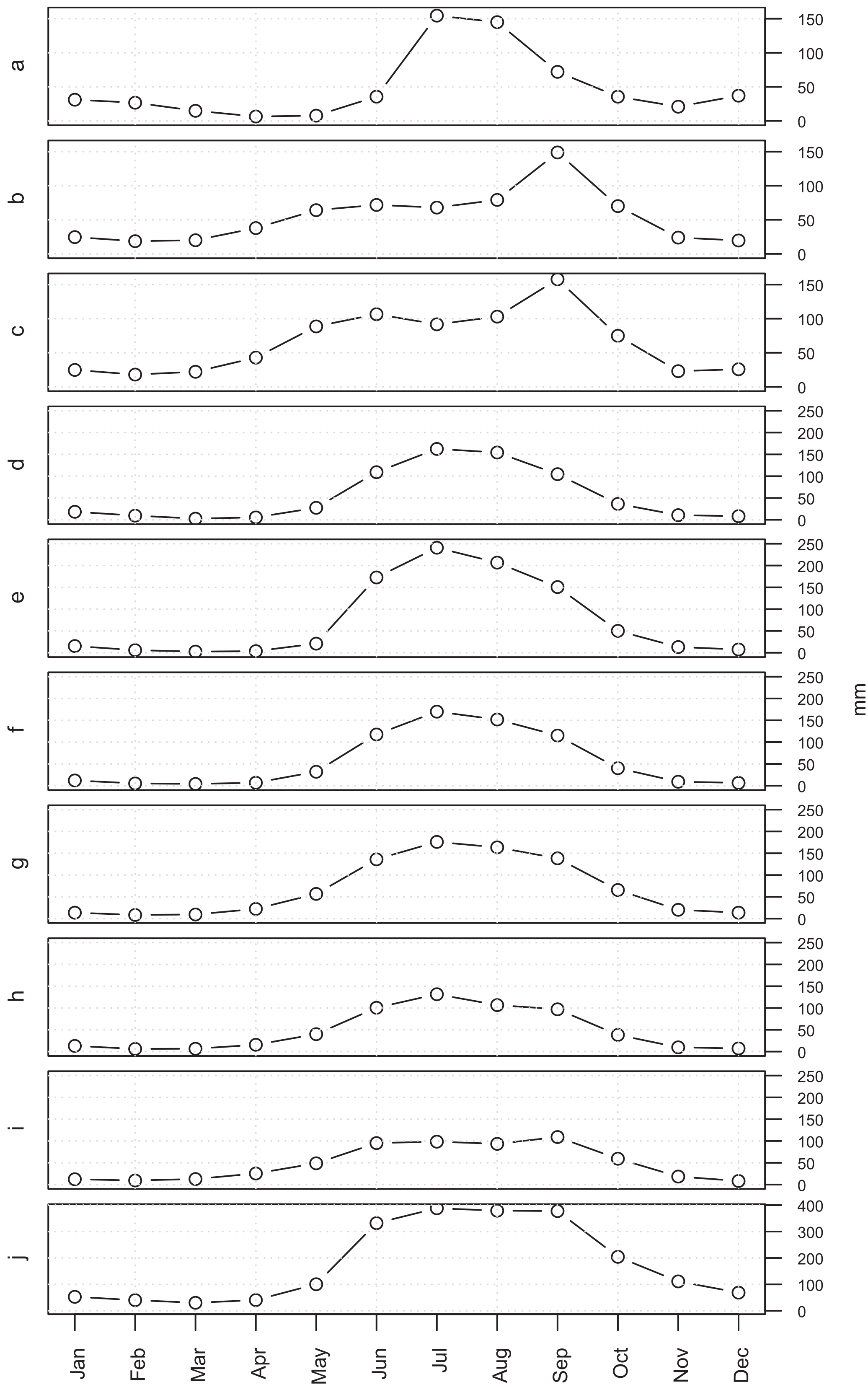

Fig. 3. Rainfall monthly mean (mm) for the ten watersheds. The period and watersheds are the same as in Fig. 2.

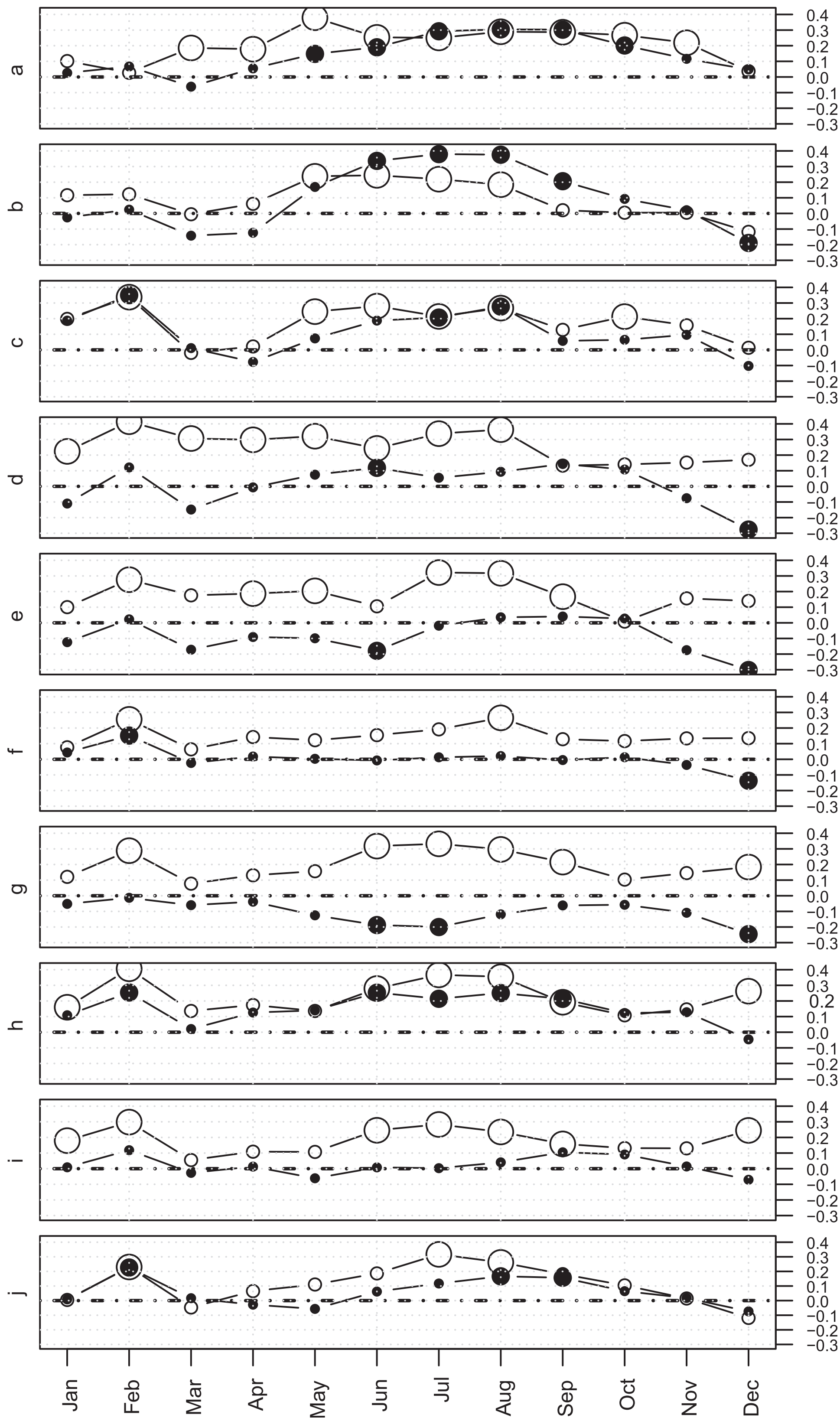

Fig. 4. Monthly minimum and maximum temperature standardized anomaly trends (per decade). Dark and clear dots refer to the minimum and maximum temperature standardized anomaly trends, respectively. The large dots mark the trends that have a significance level above 90%, according to Mann–Kendall test. Linear regression adjustment was used to calculate the slope of the trends. The period and the watersheds are the same as in Fig. 2.

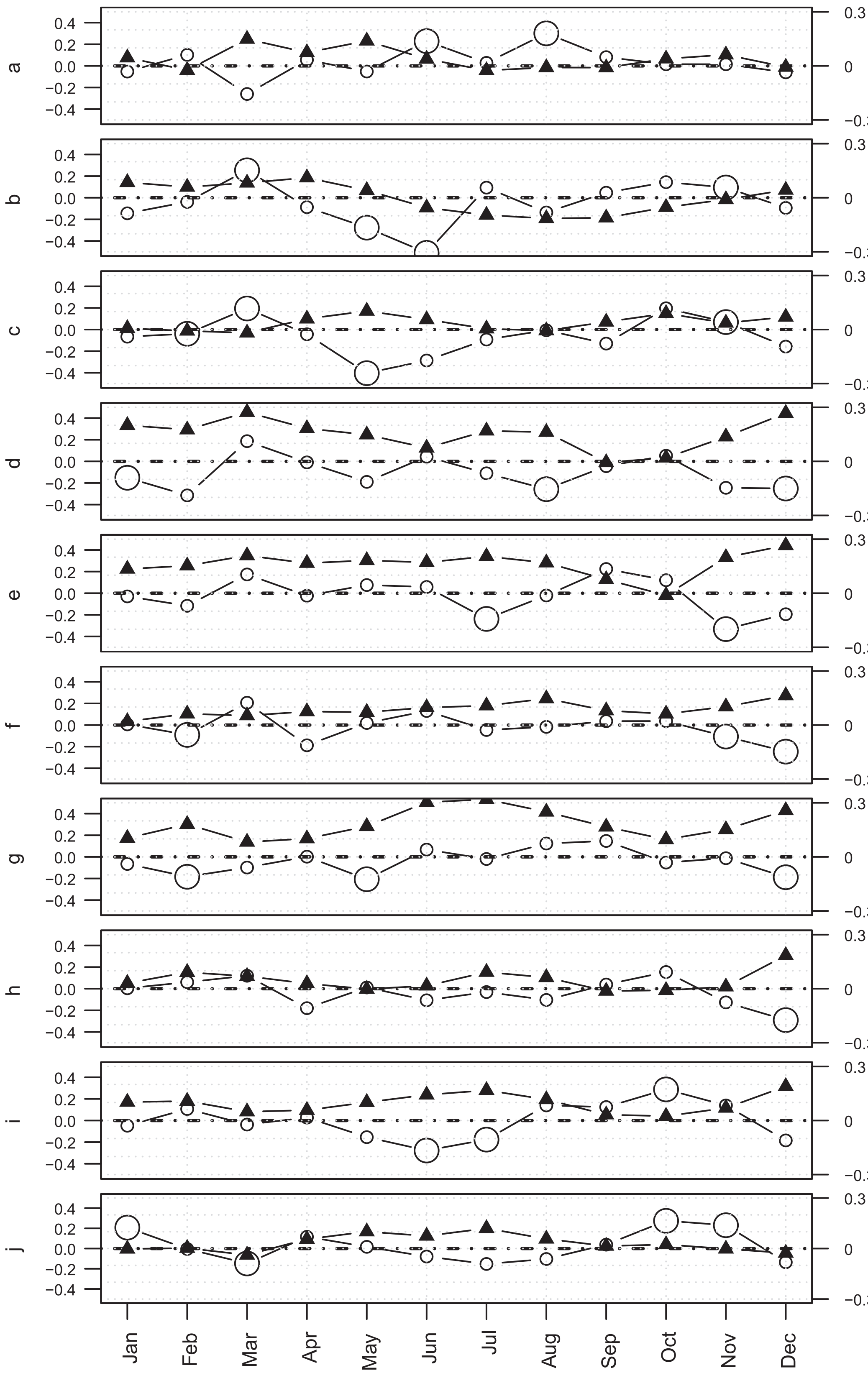

Fig. 5. Monthly precipitation standardized anomaly trends (per decade), and minimum and maximum temperature difference trends. Clear dots and the right-side scale refer to precipitation. The large dots mark the trends that have a significance level above 70%, according to the Mann–Kendall test. Linear regression adjustment was used to calculate the slope of the trend. Dark triangles and the left-side scale refer to the minimum and maximum temperature difference trend. The period and the watersheds are the same as in Fig. 2.

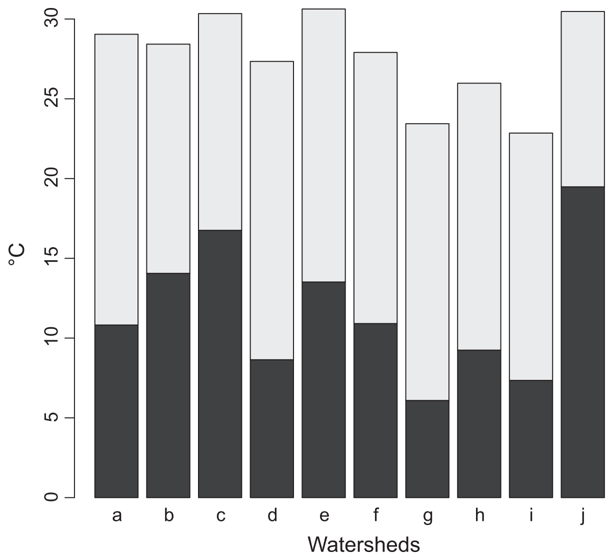

Fig. 6. Annual mean minimum and maximum temperature (°C) for the ten watersheds. Dark and clear bars represent the minimum and maximum temperature, respectively. The period and the watersheds are the same as in Fig. 2.

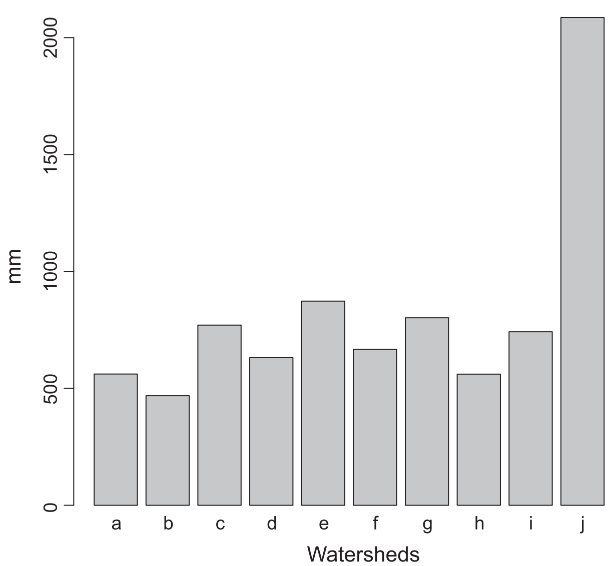

Fig. 7. Same as Fig. 6, but for total annual precipitation (mm).

$$\overline{T} = \frac{1}{40}\sum_{i=1970}^{2009} T_i$$

where T is either the maximum or minimum temperature, and i refers to year, and

$$T_i = \frac{1}{12}\sum_{j=1}^{12} T_{ij}$$

where j refers to month. The temperatures were integrated by watershed in the same way as mentioned above (Thiessen method).

The annual average maximum temperature is in the range of 24–31 °C in all watersheds. High-altitude watersheds exhibit low maximum and minimum temperatures, and are located in the central zone (Fig. 6d and f–i). The annual minimum temperature

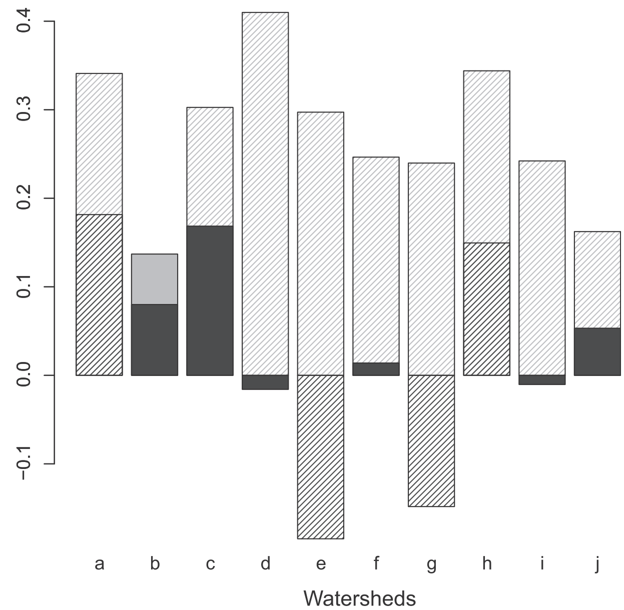

Fig. 8. Annual minimum and maximum temperature standardized anomaly trends (per decade). Linear regression adjustment was used to calculate the slope of the trend. Dark and gray bars represent the minimum and maximum temperature, respectively. The hatched bars mark the trends that have a significance level above 90%, according to the Mann–Kendall test. The period and the watersheds are the same as in Fig. 2.

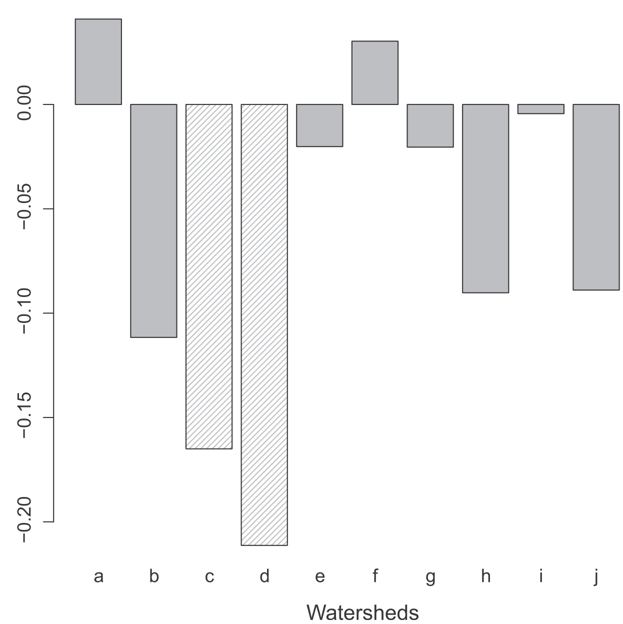

Fig. 9. Annual precipitation standardized anomaly trends (per decade). Linear regression adjustment was used to calculate the slope of the trend. The hatched bars mark the trends that have a significance level above 70%, according to the Mann–Kendall test. The period and the watersheds are the same as in Fig. 2.

shows a wider temperature range among different watersheds (7–20 °C). This wider range in annual minimum temperatures is mainly due to geographic conditions because the two watersheds with higher minimum temperatures are close to the ocean, and the inland watersheds have low minimum temperatures due to higher altitude (Figs. 1 and 6). DTR values are very similar in most of the watersheds (14–17 °C), except in Papaloapan (the most tropical region) where the difference is only 10 °C.

The annual mean rainfall ($\overline{R}$) per watershed is calculated as:

$$\overline{R} = R_{ij}\frac{1}{40}\sum_{i=1970}^{2009} R_i$$

where i refers to year, and

$$R_i = \sum_{j=1}^{12} R_{ij}$$

where j refers to month. Precipitation is then integrated by watershed, using the Thiessen method.

As expected, the Papaloapan watershed presents the highest total annual rainfall (>2000 mm) due to its tropical location. The remaining watersheds present a value of around 600 mm (Fig. 7).

3.2.2. Annual trend

Rainfall, as well as maximum and minimum temperature standardized anomalies, for each station were calculated by using annual averages and standard deviations (Wilks, 2006). Standardized anomaly data were integrated by watershed using the Thiessen weighted-average method.

Similar to monthly trends, the Mann–Kendall test was applied to evaluate annual trends and their significance levels. A simple least-square fit was used to compute the slope of temperature and rainfall annual trends. The subsequent analyses will use a 90% significance level for maximum and minimum temperatures, and 70% for precipitation.

All the annual maximum temperature trends are positive for nine watersheds, and are consistent with the data analysis on a monthly basis. However, annual minimum temperature trends show both positive (Yaqui and Laja) and negative (Santiago–Guadalajara and Lerma-Toluca) values (Fig. 8), with no indication of a large-scale signal. These results imply that regional/local factors may be the drivers of climate change in these watersheds.

Only two watersheds (Soto-La Marina and Verde Grande) have significant negative precipitation trends (Fig. 9). In a similar way than in the case for annual temperature trends, precipitation does not show a homogeneous behavior in all watersheds. This suggests, once more, that regional/local factors may be the main drivers of the observed changes.

4. Conclusions

Because of the scarcity of data, and because the influence of decadal (e.g., PDO) and/or multi-decadal (AMO) signals could be present; it is not possible to assert that the trends shown here are due to climate change. However, as this study shows, the features observed in precipitation and maximum and minimum temperatures are similar to projected climate change in Mexico. Therefore, it seems plausible to suggest that the observed trends could be possible evidence of climate change.

This work confirms that the increments in maximum temperatures in most of the watersheds are in agreement with previous climate-change studies. Conversely, the minimum temperature appears to be less sensitive to this change. Consequently, as shown, DTR has increased in recent decades.

An important result of this work is that the difference between monthly maximum and minimum temperature trends is negatively correlated with monthly precipitation trends. This suggests that LCCs could be the main drivers of climate change in the region. If in fact climate change in Mexico is mainly due to LCCs, this should spark the generation of guidelines to define land-use and reforestation policies.

All the source data and the R scripts used to generate the information in this study are available at http://github.com/juliosergio/BID2012.

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